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FINAL REPORT

COMPACT UNDERWATER BUOYANCY SYSTEM
FOR EXPENDABLE SONOBUOYS

SUBMITTED TO: NAVAL COASTAL
SYSTEMS CENTER

DATE: 31 JULY 1989

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There is need for a compact underwater buoyancy system capable of maintaining a specified (about 10 lb) weight at any preset water depth from 0 to 2,000 ft. It would be used in expendable sonobuoys where hydrophones or transducers must be kept at a preset depth. Defense Systems, Inc. (DSI) built and demonstrated such a device in Phase I, an engineering model of such a device in the form of an expanding, nested set of 6" diameter 4" long cylinders. Upon deployment and activation by a salt water switch and electronic timer, an initial expansion of the nested cylinders takes place to compensate for the payload weight. Then a microprocessor and pressure-sensor-controlled stepping motor is used to micro adjust cylinder expansion to cause the device to change buoyancy, thus maintaining depth at the preset level. The buoyancy device uses little electric power, contains no hazardous devices and has a very low projected unit cost.

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1.0 BACKGROUND

Topic # N87-67 of the 1987 SBIR announcement described a Navy need for a "Compact Underwater Buoyancy System for Expendable Sonbuoys". Defense Systems, Inc.'s proposal was selected for a SBIR Phase I award to build such a device. The original design was predicated on a set of nested cylinders that upon deployment would expand and provide the required buoyancy to support a 10 lb weight anywhere in the water column from 0 - 2000'. A microprocessor controller connected to a pressure sensor monitored the inital depth setting and would expand and contract one of the cylinders as required to cause the device to ascend or descend depending on the selected depth and to compensate for small changes in depth. The device contained a linear actuator to move the cylinder as well as the electronic circuitry and electrical power to operate the unit.

During the initial design phase of the effort, it was determined that the weight of the combined electronics and mechanical hardware in the buoy necessitated the use of more than two nested cylinders to obtain the required net buoyancy. The maximum depth requirement of 2000' drove the thickness of the metal in the walls and interlocking flanges to the point where attaining the required buoyancy was not possible due to the decreasing size of the nested cylinders and the added weight of metal required to meet the full depth capability. Also to provide sufficent force to expand the cylinder at the max depth, required a very large actuator and a prohibitive amount of electrical power.

After discussions with the COTR, Mr. Robert Manning, NCSC, it was determined that in the main application of the buoyancy device more volume could be made available for the device. It was also suggested that the electrical power to operate the system could be made available from the payload. With this information in hand a reevaluation of the design was initiated.

It was decided that to test the system concept, a reduced depth capability device would be built first and tested. It was also decided that when the cylinders are initially expanded the device would be approximately neutrally buoyant, and a small contained movable cylinder would supply the buoyancy required to adjust depth once it was at the required depth.

2.0 DESCRIPTION

The Phase I Variable Buoyancy Device (VBD) consists of an outer cylinder and a nested inner cylinder containing the microprocessor, battery housing, and motor driven buoyancy control piston. The operational sequence of the VBD is described below and depicted in the line drawing of Figure 1.

- o Inner and outer cylinders are held together by magnesium bolts (Figure 1a).
- o Magnesium bolts dissolve and cylinders are extended by internal pressure (Figure 1b).
- o Cylinders are locked in place at end of travel by a spring latch mechanism (Figure 1b).
- o VBD with payload attached is now neutrally buoyant.
- o Pressure sensor sends signal to microprocessor which determines current depth of VBD.
- o Microprocessor commands motor to extend/retract buoyancy control position (Figure 1c).
- o VBD rises/sinks to target depth.
- o Microprocessor continues to adjust buoyancy control piston to maintain target depth.

2.1 Subbuoy Design Spreadsheet

A spreadsheet (Figure 4) was created which calculates material thicknesses required for the subbuoy at various depths, the depth rate of change achievable by use of the

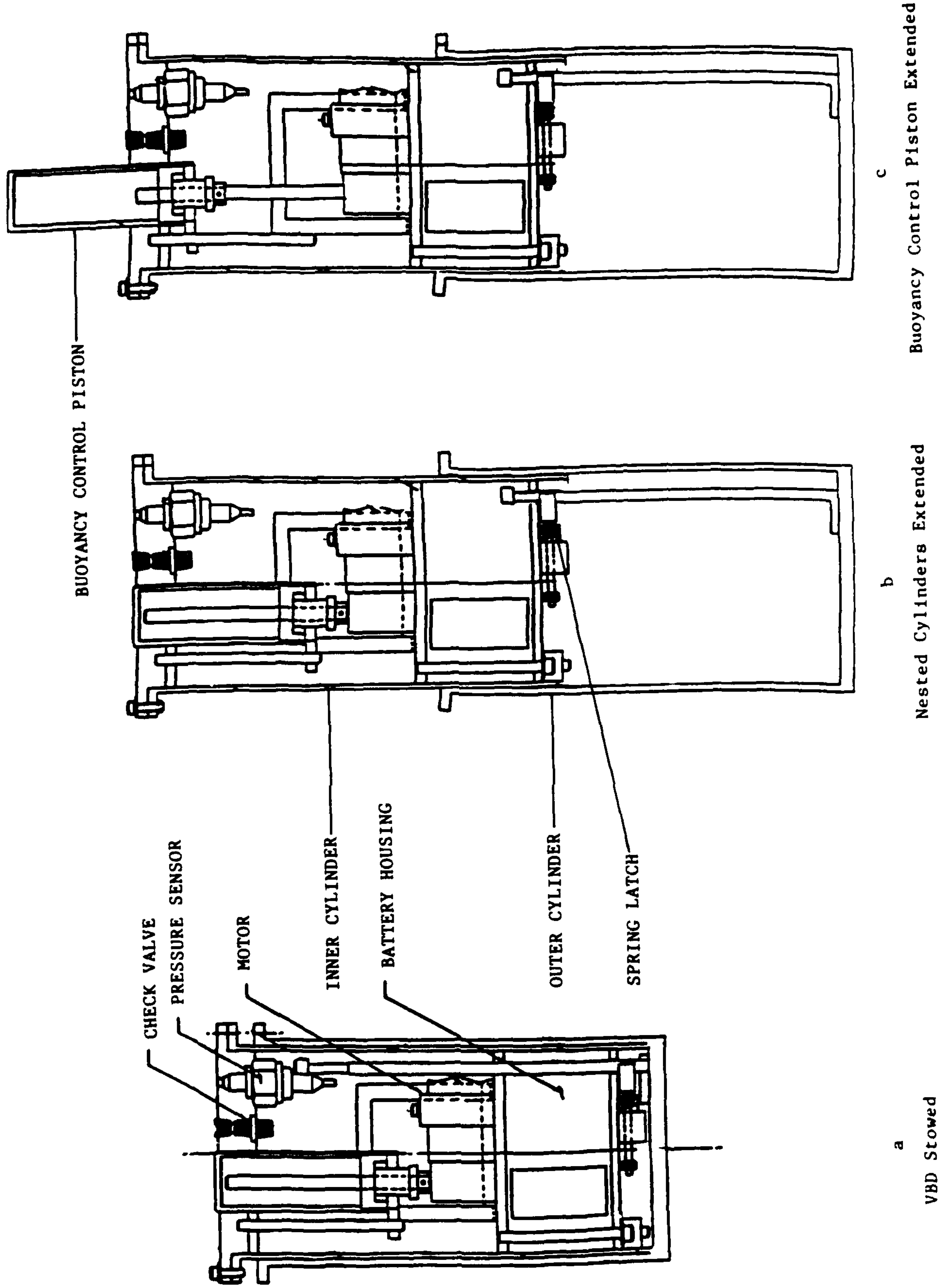

Figure (1)

Line Drawing

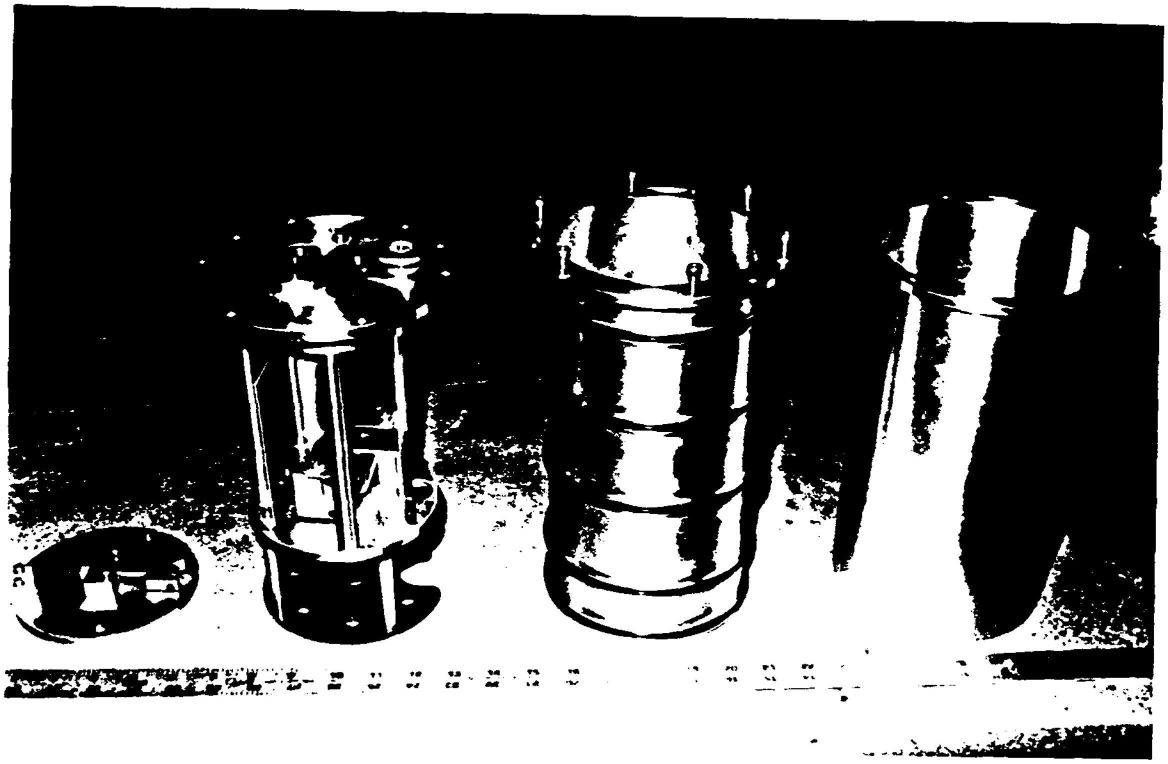

Figure (2)

Major Subassemblies of Subbuoy Prototype. (From L to R), Locking Mechanism, Battery Pack Housing With Motor Drive and Piston Assembly, Inner Nested Cylinder With O-Rings in Place, Outer Cylinder.

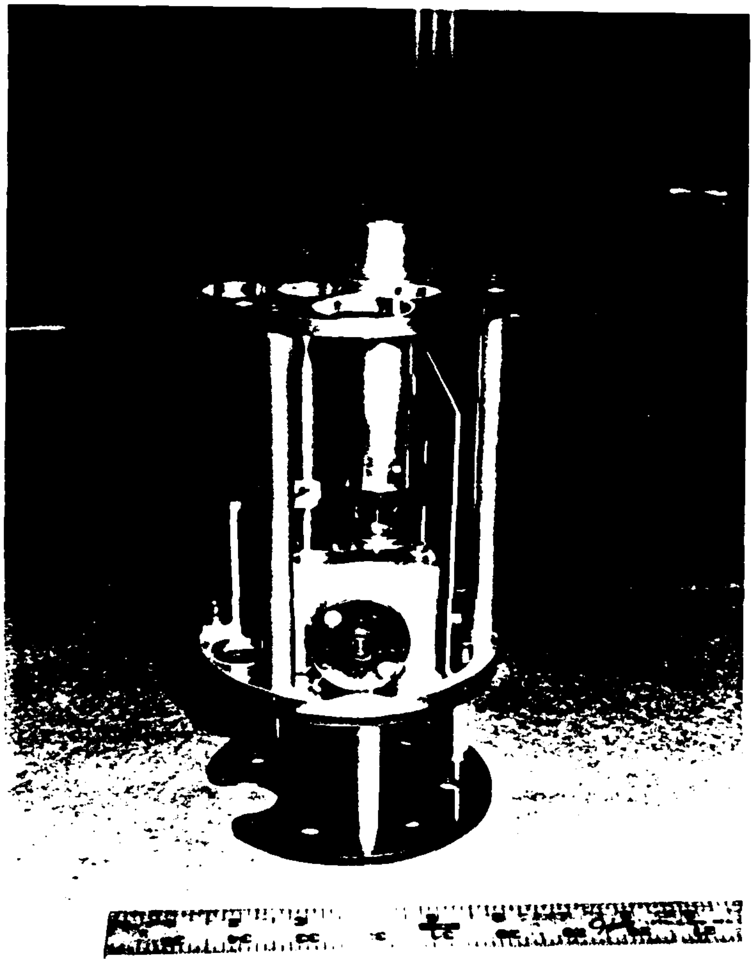

Figure (3)

Subassembly of Motor Drive and Micro Adjusting Piston Installed on Battery Pack Housing. Z Bracket at Left Will Hold Gear Driven 10-Turn Potentiometer to Measure Piston Position. Circuit Board Will Mount to Rectangular Frame at Right.

THIS SPREADSHEET CALCULATES THE WALL THICKNESS REQUIRED FOR EACH NESTED CYLINDER, THE DIAMETER OF THE CYLINDER LATCH MECHANISM, THE MAXIMUM RATE OF DEPTH CHANGE ACHIEVABLE AND THE NET BUOYANCY OR PAYLOAD CAPACITY OF THE BUOY.

SECTION 1
WALL THICKNESS VS. DEPTH

CYLINDER ID (IN)	5.75	
OPERATING DEPTH (FT)	2,000.00	
OPERATING PRESSURE (PSI)	867.00	
YIELD STRENGTH (PSI)	40000	6061-T6 ALUMINUM ALLOY
SAFETY FACTOR	1.25	
CYLINDER WALL (IN)	.078	
UPPER BULKHEAD THICKNESS (IN)	.44	
LOWER BULKHEAD THICKNESS (IN)	.46	

SECTION 2
MAXIMUM RATE OF DEPTH CHANGE DUE TO MOVEMENT OF BUOYANCY CONTROL PISTON:

SEA WATER DENSITY (SLUG/CU.IN.)	1.15e-3
SEA WATER VISCOSITY (SQ IN/SEC)	1.58e-3
PISTON DIAMETER (IN)	1.50
PISTON LENGTH (IN)	3.50
BUOYANT FORCE DUE TO PISTON (LB)	.11
BUOY COEFFICIENT OF DRAG (Cd)	1.20
VELOCITY (IN/SEC)	2.43
VELOCITY (FT/MIN)	12.13
RATE OF DEPTH CHANGE VS. PISTON DIAMETER	
RATE OF DEPTH CHANGE VS. PISTON LENGTH	

SECTION 3
MINIMUM DIAMETER REQUIRED TO PREVENT COLUMN BUCKLING OF LATCH MECHANISM:

SHAFT LENGTH (IN)	13.00	
MODULUS OF ELASTICITY (E)	3e7	STEEL
SHAFT DIAMETER (IN)	.77	
COMPRESSIVE LOAD DUE TO AMBIENT PRESSURE (LBS)	24,513.85	
AREA MOMENT OF INERTIA OF SHAFT CROSS SECTION (IN**4)	.017	
CRITICAL COLUMN LOAD (LBS)	29,924.13	

SECTION 4
NET BUOYANT FORCE (PAYLOAD CAPACITY)

	INDIVIDUAL CYLINDER LENGTH (IN)	DEPLOYED CYLINDER LENGTH (IN)	CYLINDER OD (IN)
OUTER CYLINDER	13.00	13.00	6.00
INNER CYLINDER	13.00	12.50	5.75

DEPLOYED BUOY LENGTH	25.50
DEPLOYED BUOY DISPLACEMENT (CU IN)	692.16
BUOY WEIGHT (LBS)	14.77
BUOYANCY (LB)	25.61
PAYLOAD CAPACITY (LBS)	10.84

Figure (4)

Subbuoy Design Spreadsheet

buoyancy control piston and the payload capacity for a given buoy configuration.

Section 1 of the spreadsheet calculates the wall thickness required to prevent collapse of the nested cylinders at depth. Given cylinder I.D., material properties, operating depth and factor of safety, Section 1 will output cylinder wall thickness and upper and lower bulkhead thickness using equations from "Mechanical Analysis and Design" by Arthur H. Burr. A graph of wall thickness vs operating depth is provided as Figure (5).

Section 2 calculates the depth rate of change due to the buoyancy control piston. Assuming the sea water density, piston diameter and length, and coefficient of drag for the buoy, this section will output buoyant force due to the piston displacement and the resulting velocity. Section 2 assumes that the buoy is neutrally buoyant when the piston is extended to one half its length and that buoyant force is equal and opposite to the drag force. A graph of the rate of depth change vs piston diameter and piston length is shown as Figure (6).

The mechanism which locks the cylinders in the extended position to prevent recompression consists of a spring loaded latch which engages a slender column at the end of cylinder travel.

The slender column experiences a compressive load proportional to the buoy depth and may buckle. Section 3 calculates the minimum diameter required to prevent buckling as a function of depth and calculates the critical load for the column.

Section 4 calculates the payload capacity of a two cylinder buoy configuration. The displacement and weight of a deployed buoy with cylinders extended is calculated and the difference between the two values is the payload capacity.

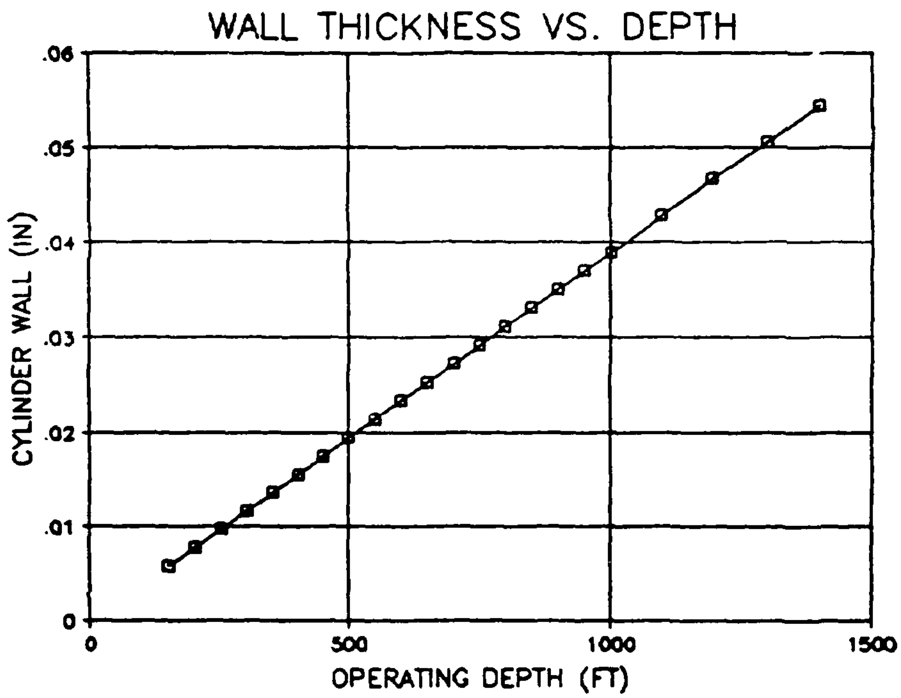

Figure (5)

Cylinder Wall Thickness Required to Prevent Collapse of the Cylinders Assuming One Atmosphere Pressure Inside the Buoy. From This Data, Weight of the Cylinders and Ultimately the Net Buoyant Force of the Buoy can be Calculated.

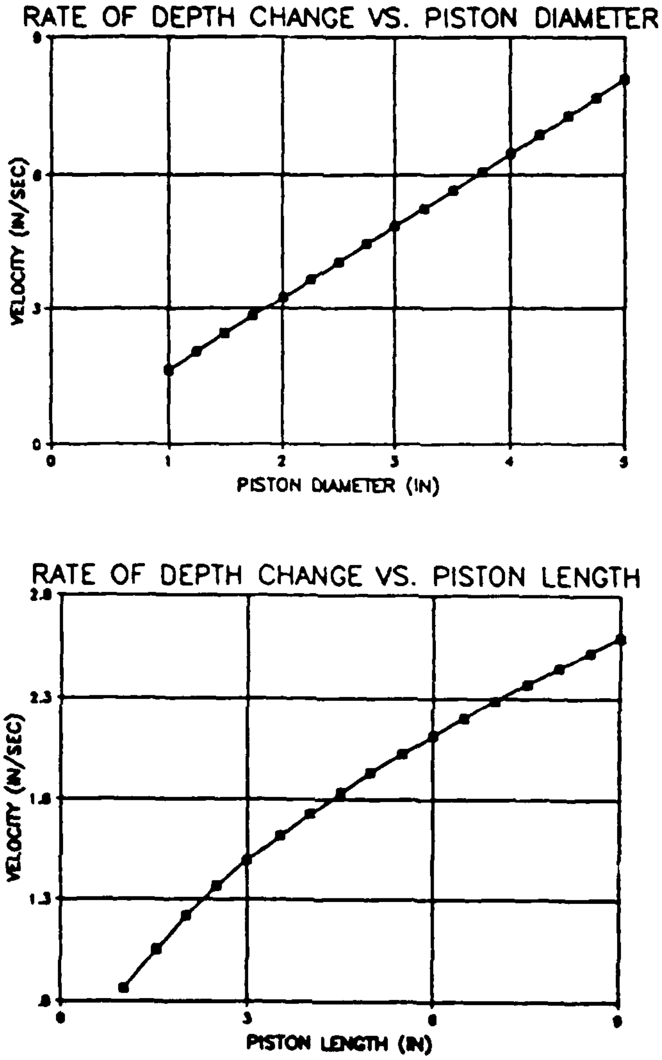

Figure (6)

Plots Show Rate at Which Variable Buoyancy Device Can Change Depth as a Function of Buoyancy Control Piston Diameter and Length. Velocities are Maximum Values Calculated With the Buoyancy Piston Fully Retracted or Extended.

Deployed cylinder length is the length of each cylinder exposed to the sea after the cylinders are extended. Using this value and the cylinder outside diameter the total displacement of the buoy is calculated.

The design spreadsheet shows that the maximum buoyant force provided by the small actuator (Figure (7)) driven piston is approximately 0.10 pounds. This will drive the unit up or down at approximately 12 feet per minute. The payload capacity will be approximately 9 pounds, depending on the final weight of the device. For testing, the unit was ballasted by submerging in water (nested cylinders expanded and the small piston extended halfway) and adding weight until neutral buoyancy is achieved. A tapped hole is provided in the bottom end cap for attachment of ballast weights.

2.2 Electronics Description

The electronic circuitry to operate the system was designed but hardware was not assembled as part of the Phase I effort. A description of the system operation is provided below. Schematic shown as Figure (8).

The floater-controller is designed to operate the link motor in the floater that will control the buoy displacement, and thus the float depth. A link position potentiometer is provided to allow a position feed-back for the controller of the current position status of the displacement. A pressure sensor is included to allow a measurement of the current depth of the floater. These two sensor inputs provide the necessary inputs for the controller. A digital motor controller operating as a DC motor controller is used to provide bi-directional activation of the motor and thus direct operation of the floaters buoyancy. The floater-controller has direct control of the power switch and can minimize power consumption by turning off the sensing and motor drive circuits. In addition, the controller includes a dip-switch option select input to allow different operations to proceed as necessary for the system testing. A serial-port is also included to allow commands to a sealed unit for additional

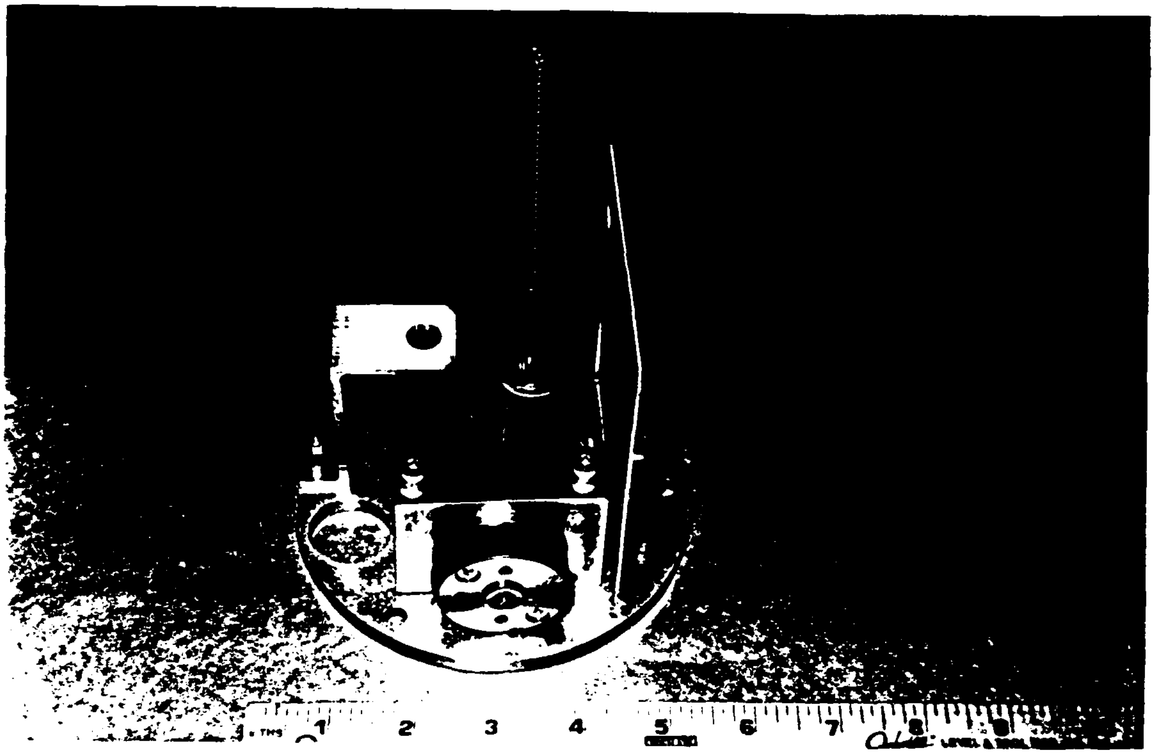

Figure (7)

24V DC Motor and Worm Gear Which Will Drive Piston to Fine Tune Buoyancy.

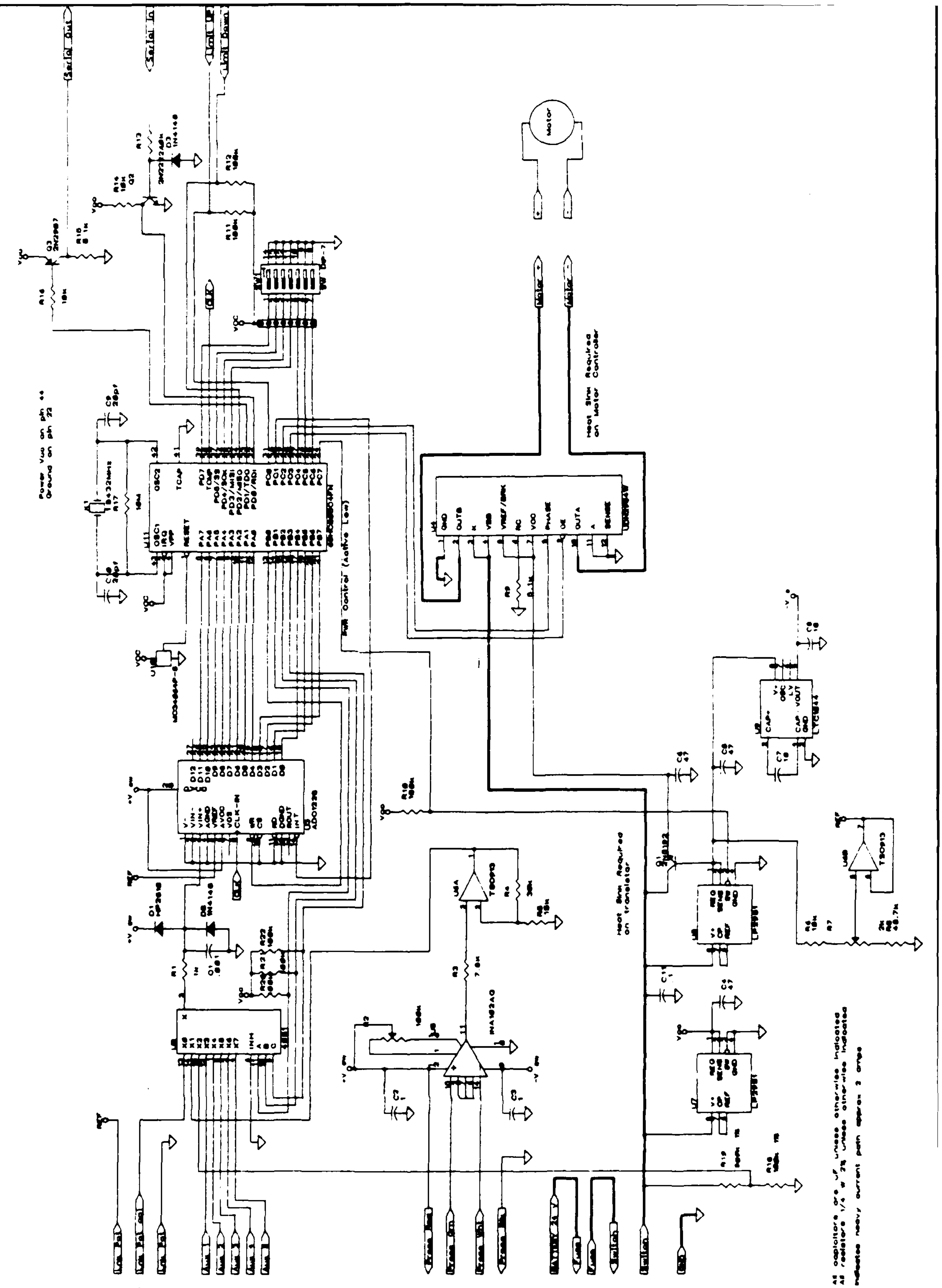

Figure (8)
Microprocessor Control Schematic

testing and control without disassembling the unit during a field test.

The microprocessor is a single chip controller with on-board RAM (176 bytes) and ROM (4K bytes). The 68HC805C4 includes a hardware UART for the serial-communications in addition to 3 1/2 I/O ports for control of various bits to operate the system. Twelve bits of the I/O port are used for a parallel bus to the 12 bit A/D converter that is used for both measurements of the link pot position, and measurement of the pressure sensor output.

The ADC1225 is currently used with the Asynchronous Serial Interface Device (ASID) module for conversion of pressure depth and temperatures. This unit provides an easy-to-use 12 bit converter to measure the pressure sensor with .07 meter (.25 foot) resolution over a wide range from 0 (surface) to 1000 feet. The link-pot voltage can be measured with up to 12 bit resolution if required to monitor small adjustments by the motor.

The pressure sensor is a strain gauge bridge type sensor. The strain-gauge bridge is amplified by an instrumentation amplifier and a gain-set amplifier will provide a voltage input to the Mux - A/D circuits for measurement by the controller.

The reference voltage to the A/D converter is adjustable to allow setting the pressure range to minimize tweaking the controller software to attain the control range and setting accuracy required.

The link-pot is a relative measurement (ratio-metric) of the pot position. The pot desired is a linear throw element that can follow the actuator arm driven by the motor. The output will thus be a measure from 0% full throw to 100% full throw. This primarily provides an input to the controller so that the controller will "know" where the actuator position is, especially during power-up. It will also be necessary to provide actuator position information to the controller to prevent overrunning the actuator arm. (Possibly limit switches may be used to provide overrun protection, however the status of the limit switches must be provided to the controller in the event that the link-pot is not available in this design.) The motor-controller is a single chip device with a large heat-sink tab. The UDN2954W provides up to 3.5 amps of current (2 amp continuous) to the motor. It is desired that the motor voltage be selected to provide 24 volt operation. This will reduce the current required to operate the motor while providing the maximum power to the motor. The internal voltage drops of the controller (up to 1.5 volts) will become a small percentage of the voltage supplied to the motor. The system is expected to require about 400 ma of drive power under most conditions requiring initial setting of the actuator arm, however a higher current up to 1.7 amps is expected under full load on the actuator arm. If this system were to be operated at 12V (not recommended) then the required current will be nearly double, which will place the motor controller over its current limit under full load. The voltage drop across the motor controller will reduce the voltage to the motor to nearly 10 volts with a fully charged battery. This will result in poor operation and possible failure of the system.

The power to the system is regulated by two regulators and a voltage inverter. The reference voltage to the A/D is derived from the switched power supply. A fixed 5V power is provided to maintain the computer power. A switched 5V supply is provided to maintain the computer power. A switched 5V supply is provided to power the A/D converter, the OP-AMPs, as well as provide a switch signal to the motor-controller logic-sw-pwr. This switched power also provides the reference voltage. By switching the power off, the current required to operate the system is reduced to about 1-2 milli-amps. As a result the system (which will be idle most of the time) can conserve battery power for the bursts of energy that are needed to set the actuator when required. When the motor is not running and the switched power is turned on to measure the pressure of link-pot position the current required will increase to about 30 ma. These measurements are generally of short duration thus with a low duty cycle which will allow minimum power requirements. Average system power requirement is estimated to be less than 10 milliwatts.

Due to the compact design of the device, lithium cells had been selected to allow the highest energy density. To provide safe operation (without overstressing the batteries) 7D cells have been selected that will provide 2 amps continuous (if necessary under full load) and will have a 12 amp-hour capacity. The cells are arranged in a circular pack of 7 cells. The cells, wired in series, are placed at one end of the device with a removable cap to allow easy battery replacement without opening the main electronics compartment. In view of the current plan to use electrical power from the payload, the battery pack will be ommitted from the Phase II design.

An array of dip switches are provided to allow operator selection of different operation programs, such as testing in one mode, and operation at some preset depth as another mode. In addition a serial port will be provided to allow communication with the controller from an outside host computer (or lap-top) to assist in communication with the system during testing. This is primarily to allow options to be selected without opening the container and is not required during free deployment float test. Since the status of the system is not always apparent from the outside, the serial-communications will be used to determine the systems current state. The serial-communications are also used for manual operation to test the unit. The exact operation of this test feature will be developed as need requires.

2.3 System Operation

The system operation will proceed from initial power application via the switch by performing the following actions:

1. Initialize the computer for proper I/O definitions.

2. Shut down the motor, and place system in low power mode.

3. Check the current settings of the option dip switches and begin proper operation.

Switches:

0000000	Automatic operation.
1000000	Manual operation.

The remaining switches may be used to set various program operations for testing the unit. It is unknown at this time what actions may be desired.

4. If automatic operation is desired, then wait for one of two possible actions:

   A. Sample the current pressure at least once a second and prepare to deploy to the preset depth if the pressure is changing.

   B. Monitor the serial port and prepare to take a desired action depending upon what command has been received.

      If the command is to place the unit in the manual mode of operation then only perform an action if the command is received.

      If the command is to place the unit in the automatic mode of operation then watch the pressure changes and prepare to deploy to the preset depth.

5. If manual operation is desired, then wait for a command and take the desired action. The commands are ASCII characters that are transmitted by a host computer to the system.
   Commands:

   U   Activate the motor while the U command is being received, or until maximum extension has been obtained and extend the unit to raise the unit to a new depth, or surface the unit.

D Activate the motor while the D command is being received, or until minimum extension has been obtained and retract the unit to lower the unit to a new depth.

S Sample the sensors and report the current data for the link-pot voltage, pressure sensor value, and battery voltage and option selection.

R Reset the system, read a new option selection and restart the operation.

L Load a new word into the option-select register. This performs the same function as the dip switches but allows the operator to set a new dip switch value via the serial-communication line.

2.4 Automatic Operation

The automatic operation is intended to allow the unit to deploy to a preset depth (option selections) and hover within a few feet at the preset depth.

The automatic sequence is currently designed to function from a surface deployment. The unit will perform periodic pressure measurements at about a 1 second rate and will sense when a pressure change has occurred. This will indicate that the deployment is under way. The unit will begin by retracting itself to sink. Pressure measurements are continuously updated as the sinking proceeds.

When a trigger depth is reached the unit will attempt to extend itself to set the buoyancy to neutral, and thus slow its decent. If slowing does not occur then the unit will attempt to correct the decent by extension until full extension is reached. The unit should slow down the decent or rise toward the surface. The unit will attempt to maintain a depth setting using the fast sampling for a few seconds up to 3 minutes. This will allow the system to stabilize at some preset depth.

When the hovering stops the pressure sampling will proceed at a slow sample rate of once every 15 seconds to sense pressure changes above or below the trigger depths. The motor will operate only if the trigger depths are exceeded to attempt to balance the unit at the desired hovering depth. This hysterisis will help to maintain low power consumption and prevent hunting as the unit hovers.

A simple simulation of the depth seeking and hovering process is attached as Figure (9). The BASICA program assumes that the unit moves at full speed (piston fully extended or retracted) until close to target depth, then begins to fine tune the piston when within a preset distance from target depth.

The depth seeking process is highly damped; in other words, the ratio of frictional forces (hydrodynamic drag) to drive force (piston adjustments) is high. For this reason, convergence to target depth will be slow but controlled, with little chance of overshooting.

3.0 TEST OBJECTIVES

The objectives of the Phase I test program were as follows:

1. Test the functioning of the buoyancy control mechanism including:

    A. Rise/Sink performance.
    B. Suitability of actuator motor to drive buoyancy control piston.
    C. Integrity of dynamic O-ring seal.

2. Test functioning of entire buoy system including:

    A. Buoy attitude during ascent, descent and hover.
    B. Integrity of static O-ring seals.

3. Determine payload capacity.

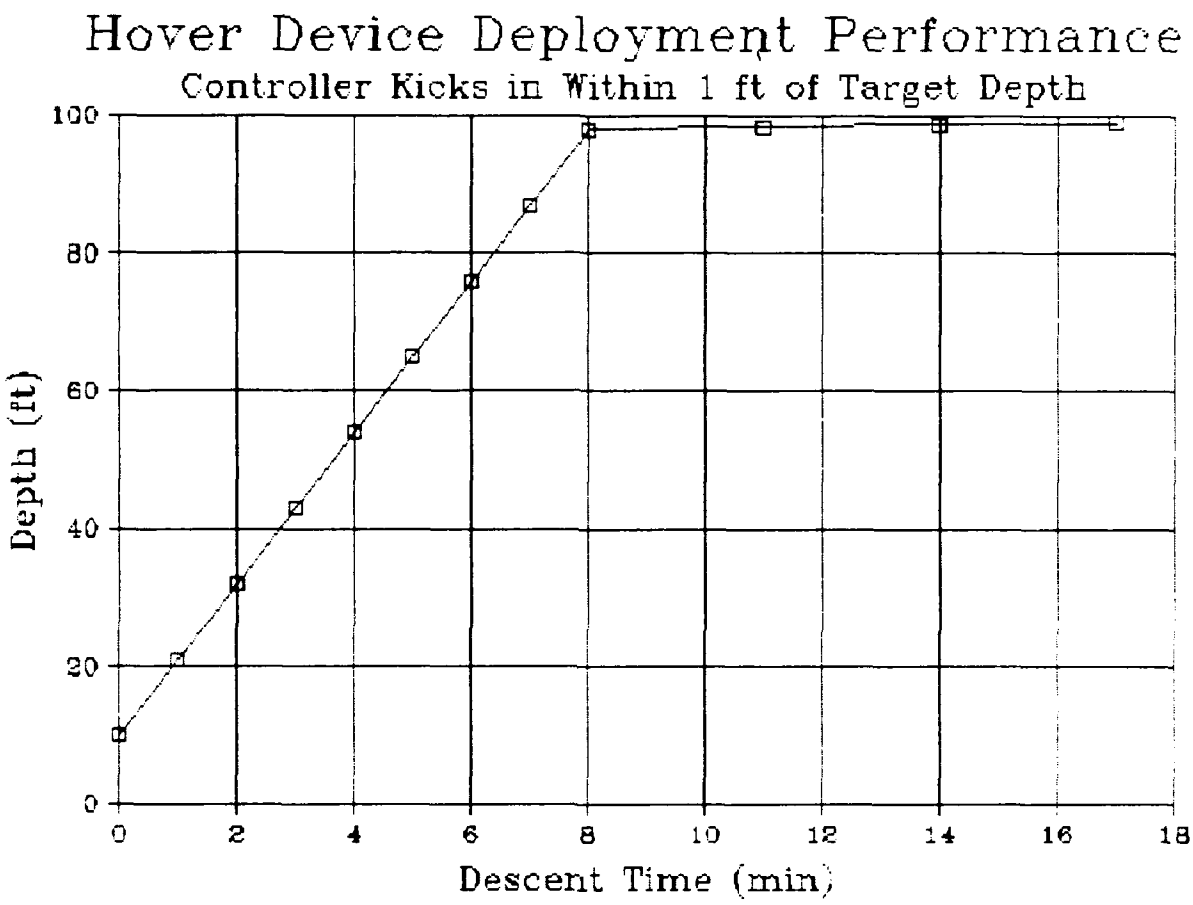

Figure (9)

Underwater Buoyancy Device Simulation Output

Functions of the buoyancy control mechanism tested were the rate of depth change achievable with the piston fully retracted and extended and the motor force available to overcome both the O-ring seal friction and the pressure differential while operating at depth.

The payload capacity was determined by weighing the amount of ballast added to achieve neutral buoyancy with the nested cylinders deployed.

Attitude of the buoy was observed during shallow water tests and O-ring integrity was determined by post-test disassembly and inspection.

3.1 Test Apparatus

Equipment used during Phase I testing included the Variable Buoyancy Device (VBD), a 24V DC battery, a three position switch to operate the electric motor, 50 feet of 24 gage wire, and a water tight connector. The ballast consisted of 17 hollow steel cylinders .75 inches in diameter and 4.00 inches long open at one end and attached to the lower half of the outer cylinder of the buoy. Each hollow cylinder could be opened or closed to the water environment by removing a stopper and acted as a typical ballast tank allowing for fine adjustment of buoyancy prior to in-tank testing. All testing was conducted in fresh water.

3.2 Work Procedures

Prior to operation in water, the buoyancy control mechanism was bench tested and the buoy assembled with nested cylinders deployed. The motor and buoyancy control piston were driven by a three-position switch and DC battery source. The ballast was adjusted to neutral buoyancy of the assembled buoy.

After achieving neutral buoyancy, the VBD was placed in the pool with the buoyancy control piston fully extended. The piston was then fully retracted and the VBD was video taped as it descended. Upon reaching the bottom, the piston was fully extended and the buoy video taped as it ascended and hovered for three minutes before being brought up to the surface and removed from the tank. This procedure was repeated and the rise/sink rate was observed.

After testing, the VBD was disassembled and inspected to determine if any leaks had occurred at the O-ring seals.

3.3 Test Results

Positive Results

1. A closed loop variable buoyancy system consisting of a motor-driven piston was developed and tested.

2. A rise/sink rate of 20 feet per minute was achieved.

3. The buoy hovered at a set depth for three minutes.

4. The prototype payload capacity of 4.4 pounds agreed well with the design spreadsheet prediction.

5. The buoy maintained an upright attitude during ascent, descent and hover.

6. No leaks occurred at any seals.

Negative Results

1. The off-the-shelf motor made by Motion Systems and used to drive the buoyancy adjusting piston jams easily at the end of piston travel, however when under microprocessor vice manual control, piston movement will cease prior to reaching the end of travel.

2. Due to the small buoyant force generated by the buoyancy adjusting piston, neutral buoyancy must be achieved within close tolerances.

4.0 CONCLUSIONS

1. The motor driven buoyancy compensating piston proved to be a workable concept for adjusting buoyancy.

2. The deployed size of the buoy needs to be increased or buoyant weight reduced to achieve a 10 pound payload capacity. Supplying electrical power from an external source will reduce buoy weight.

3. The volume of the buoyancy compensating piston must be increased to compensate for expected changes in seawater density and to open up the tolerance required to achieve neutral buoyancy.

4. The length of 24 gage electrical wire attached to the VBD and used to control the motor probably affected the rise/sink rate.

5.0 RECOMMENDATIONS

1. An autonomous test should be conducted to eliminate the effect of the electrical wire on the rise/sink rate. This test will provide the impetus to develop the circuit board and software described in the VBD Phase II proposal and permit deep water testing to be conducted.

2. The rapid expansion of the nested cylinders using pressurized gas to equalize internal/external pressure will greatly reduce flange and cylinder wall thickness requirements and will reduce system weight. This technique will also permit the use of additional nested cylinders to provide the required buoyancy of 10 lbs.

3. The power requirements of the VBD will be supplied by an external source as indicated by the COTR.

4. A secondary source of positive buoyancy (an expandable/releasable gas bag) and a source of negative buoyancy in the form of a releasable weight should be added to the system. This will cause the device to rise/sink at a high rate (7'/second) until the preprogrammed operational depth is reached. Once at depth, release of the secondary source will cause the device to hover at the selected depth with fine buoyancy adjustment provided by the movable piston during the buoy's operational life.

A 24 volt DC source and a small cylinder of pressurized gas located externally will provide power to the buoyancy control motor. The power source and gas bottle will be designed to have an in-water weight of 10 lbs to represent the weight of the anticipated payload.

5.1 Relationship With Future Research or Research and Development

Success in Phase II research and development will lead to the capability of manufacturing small, low-cost production units. These devices will have applicability toward a family of expendable devices requiring a method of suspending a payload accurately in the water column.

A sucesssful Phase II effort will result in a subsystem that can be interfaced to various countermeasure systems currently in development.

5.2 Potential Post Application

The development, if successful, could not only lead to a device the Navy could immediately use but would also lead to a commercial product for the Company, which sells oceanographic equipment and drifting buoys.

The device also has applications in other parts of the government. Examples of these are in oceanography.

6.0 DISTRIBUTION LIST

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